Radiative Transfer in Submerged Macrophyte Canopies

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LONG-TERM GOALS

The goals of this study are to develop models of radiative transfer for optically shallow waters with benthic substrates colonized by submerged aquatic vegetation (SAV). The models will enable prediction of upward spectral radiation from the seafloor, thereby permitting (i) the use of optical remote sensing to retrieve bathymetry, (ii) the search for submerged objects of anthropogenic origin and (iii) the mapping of submarine resource distribution and abundance in coastal waters. These models will also have important applications for predicting irradiance levels within submerged plant canopies, leading to better understanding of light requirements and primary productivity of these important resources.

OBJECTIVES

Specific objectives of this study were to:

- Develop radiative transfer models of seagrass and seaweed canopies *in situ* that account for canopy architecture, impacts of water motion and bottom reflectance from the canopy/substrate complex,
- Use the resulting models of bottom reflectance to develop hyperspectral remote sensing algorithms of SAV composition, abundance and depth distribution, and
- Evaluate the utility of the remote sensing algorithms to retrieve bottom reflectances in both extremely clear oligotrophic waters and in more turbid waters characteristic of eutrophic temperate coastal and estuarine environments.

APPROACH

The work involved development of mathematical descriptions of canopy architecture, reflected upwelling irradiance, light absorption and photosynthesis from direct field observations and laboratory measurements. A system of coupled equations generated from these measurements were solved for specific scenarios of canopy structure and water column optical properties to evaluate the effects of spectral light quality and flux density of the downwelling irradiance on spectral reflectance from the seafloor boundary and whole canopy production. Model predictions of benthic reflectance and water-leaving radiance are tested against *in situ* measurements to assess the degree of closure achieved between theory and observation.

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14. ABSTRACT
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WORK COMPLETED

In the first year, canopy architecture for the eelgrass meadow growing at Del Monte Beach, Monterey, California was characterized. A model of vertical canopy architecture wad developed and expanded in Years 2-4 to include the effects of flow on canopy architecture and spectral distribution of irradiance within the canopy in Monterey Bay, California and Lee Stocking Island, Bahamas. Years 3 and 4 continued to evaluate inherent optical properties of individual submerged plants for the canopy model, measurement of bottom reflectance over submerged plant canopies using the Diver-Operated Benthic Bio-Optical Spectrometer (DOBBS) and measurements of remote sensing reflectance over submerged plant canopies using a hyperspectral tethered spectroradiometer buoy (HTSRB). Year 5 focused on refinement of the optical model to include the effects of light scattering by the canopy and water column and further development of remote sensing algorithms for bathymetry retrieval and vegetation mapping with hyperspectral remote sensing datasets.

RESULTS

The Seagrass Canopy Model. The radiative transfer equation is solved using 2-flow simulation. In addition to computing the irradiance absorbed by the seagrass canopy, the model calculates the canopy leaving irradiance for use in estimating irradiance reflectance from the vegetated seafloor. Model predictions of spectral irradiance in both the downwelling (E_d) and upwelling (E_u) hemispheres were tested against irradiance spectra measured *in situ* with the DOBBS. When parameterized with the appropriate data for canopy architecture (canopy height and vertical biomass distribution, shoot leaf area, shoot density, and leaf optical properties), model predictions of downwelling irradiance spectra were within 5% of DOBBS measurements in both the clear waters of Lee Stocking Island, Bahamas and the much more turbid environment of Elkhorn Slough, in Monterey Bay (Fig. 1A, C). Since more than 95% of the vertical reduction in E_d results from absorption by seagrass leaves and not the water column, agreement between modeled and observed irradiances indicates that light absorption, and therefore canopy photosynthesis, can be modeled accurately from knowledge of canopy architecture and leaf optical properties.

The model accurately predicted the shape and amplitude of $E_{u,}$ as well as the increase in E_u with distance above the seafloor, in the lower half of the 40 cm canopy at Lee Stocking Island (Fig. 1B). However, it under-predicted E_u by 37% at the top of the turtlegrass canopy. In Elkhorn Slough, the model accurately predicted E_u up to 25 cm above the seafloor, but under-predicted E_u at the top of the 1-m eelgrass canopy by 75% (Fig. 1D). In addition to underestimating E_u, the spectral peak in modeled E_u was blue-shifted almost 30 nm relative to the DOBBS measurement. The older eelgrass leaves from Elkhorn Slough were heavily epiphytized by diatom films, and their contribution to leaf optical properties were not included in this simulation. Clearly, epiphytes can significantly modify the optical signature of seagrass leaves *in situ*, and we are continuing to investigate this effect in collaboration with L. Drake and F. Dobbs at Old Dominion University. The predicted E_u is also very sensitive to the scattering phase function for the seagrass leaves. In the example presented here, the leaves were assumed to be bi-lambertian scattering surfaces in both the forward and backward directions. Although clearly an over-simplification this common assumption for plant canopies is thought to introduce relatively little error with respect to predicted upwelling radiances (Shultis and Myneni 1988; Ganapol and Myneni 1992, Mobley e*t al*, in review). Improving our prediction of E_u emerging from these submarine plant canopies, however, will require more detailed investigations into leaf scattering properties.

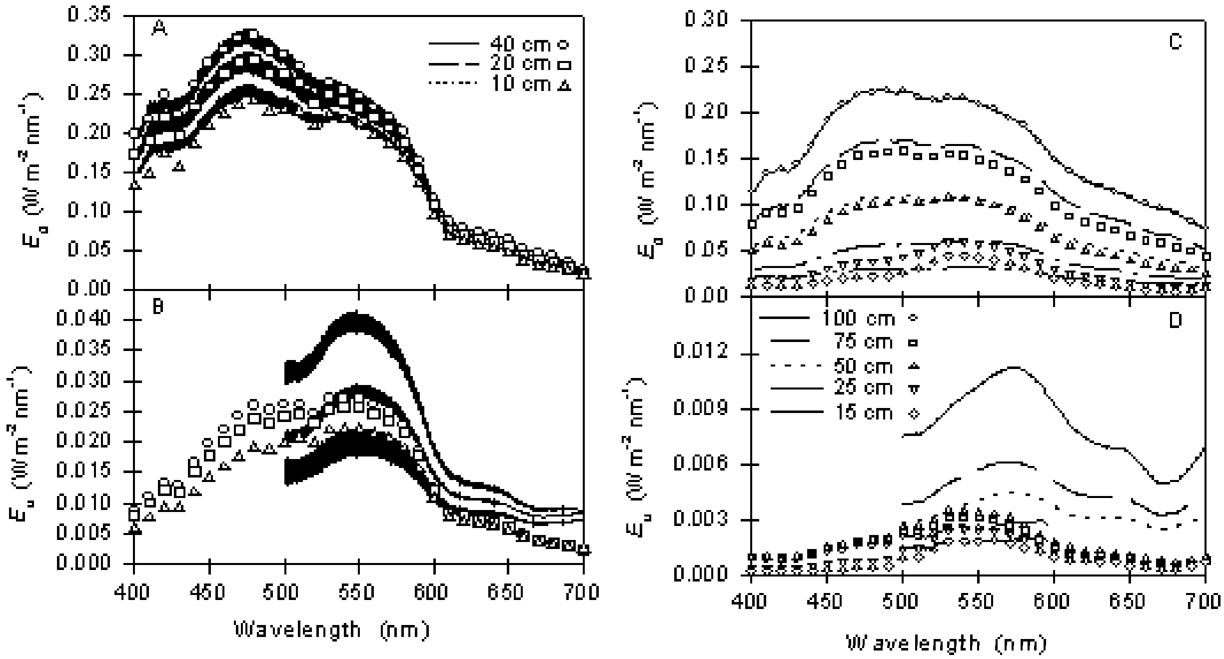

Figure 1. Modeled (symbols) and measured (lines) irradiance spectra in seagrass canopies at Lee Stocking Island, Bahamas (A & B) and Elkhorn Slough, California (C & D). Error bars on measured spectra in Figs A & B represent standard errors. Although the model accurately predicts measured E_d in both environments, it underestimates E_u relative to DOBBS measurements in the upper half of both seagrass canopies. A better understanding of the scattering properties of seagrass leaves will be required to achieve closure between modeled and measured irradiance spectra.

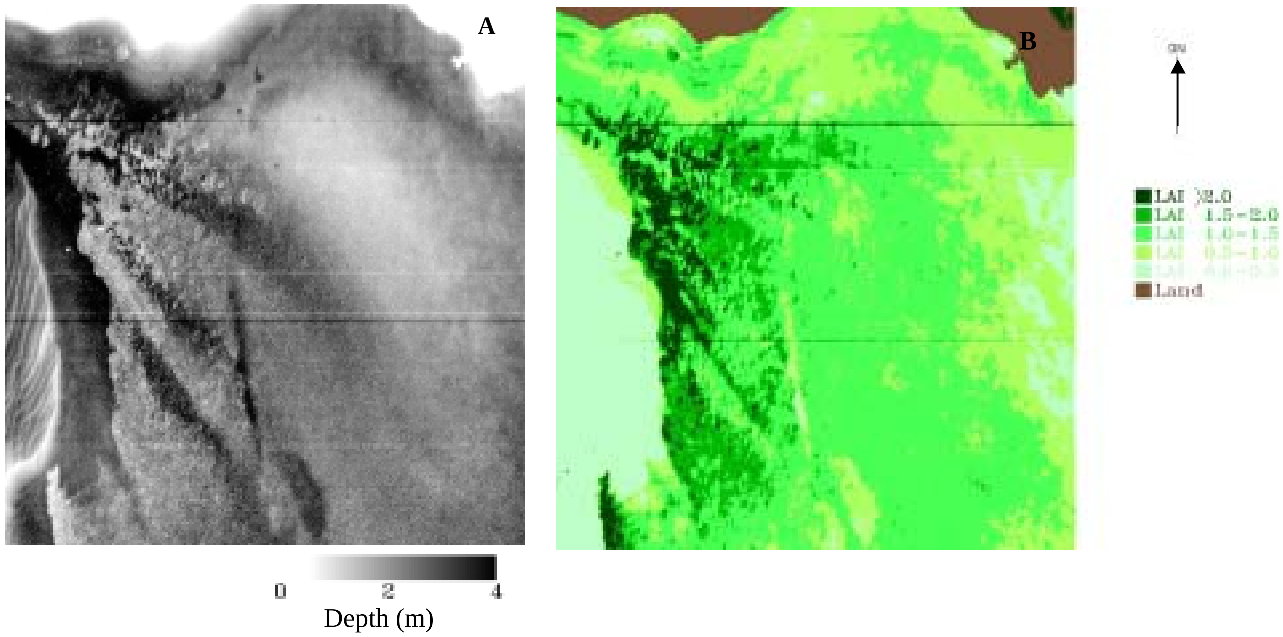

Figure 2. A. Bathymetry map of the Channel Marker region near Lee Stocking Island derived from the bathymetry algorithm reveals a sharp boundary between the migrating ooid dunes and the shallow vegetated plain cut by a series of narrow channels running SE to NW. B. Map of turtlegrass density (LAI) derived from the R_b retrieval algorithm reveals a complex pattern of dense vegetation along the boundary with the migrating ooid field grading into lower and more uniform density toward the island.

Bathymetry Algorithm. Using HTSRB observations from spot and transect surveys around Lee Stocking Island in 1999 and 2000, we were able to develop a second order regression model to achieve bathymetry by ratioing the remote sensing reflectance (R_{rs}) at 555 nm to that at 670 nm:

$$z = -0.1706x^2 + 0.8913x - 0.2316$$
$$x = \log\left[\frac{R_{rs}(555)}{R_{rs}(670}\right] \tag{1}$$

This model, which explained over 97% of the variation in all HTSRB depth observations, was applied to the PHILLS hyperspectral remote sensing data from Lee Stocking Island. The resulting image revealed considerable bathymetric structure across the study area. Important features include migrating sand waves in the ooid dune field at the eastern boundary of the study site and an undulating pattern of wide shallow ridges separated by narrow channels in the area of dense seagrass vegetation (Fig 2A).

Seagrass Density Algorithm. The retrieval of bottom reflectance from PHILLS estimates of R_{rs} was accomplished using a simple derivation of Beer's Law to estimate the spectral bottom reflectance (R_b) from estimates of water depth (z) and attenuation coefficients derived from radiative transfer simulations using measurements of water column inherent optical properties provided by Zaneveld et al. (2001):

$$R_b(\lambda) = t(a,w) \cdot Q \cdot R_{rs}(\lambda) \cdot \frac{\exp\left[-K_u(\lambda) \cdot z\right]}{\exp\left[-K_d(\lambda) \cdot z\right]}. \tag{2}$$

The transmittance of light through the air-water interface [$t(a,w)$] was approximated as 0.54 (Mobley 1994). The seafloor was assumed to be lambertian, thus Q was approximated to π. R_b was then related to leaf area index (LAI) of seagrass vegetation measured by divers at specific locations using linear regression analysis. The resulting map revealed a complex distribution of high density (LAI > 2) turtlegrass along the margin of the unvegetated ooid shoal grading into progressively lower, and more uniform densities toward the shore of Lee Stocking Island (Fig 2B).

Hyperspectral Characterization of Submerged Aquatic Vegetation. Using radiative transfer predictions of R_{rs} at 550 nm, we were able to distinguish among macrophyte taxa, sand, and optically deep water to about 2.5 optical depths using a minimum difference threshold of 4% (Figure 3A). Similarity in the reflectance signature of brown and red algae at 550 nm made their R_{rs} signatures indistinguishable regardless of water clarity or depth. However, these taxa are distinguishable at 570 nm although at a shallower optical depth than for other comparisons. Variations in the detection depth limit for different comparisons were a function of the contrast in R_b among these different targets. Consequently, the ability to distinguish submerged targets as a function of optical depth depends on the contrast in reflectance from their surroundings, which can be described by a single logarithmic function encompassing a range of water types from very clear ([Chl *a*] = 1 mg m^{-3}) to very turbid ([Chl *a*] = 10 mg m^{-3}) waters (Fig. 3B).

IMPACT/APPLICATIONS

The computation of radiant energy distributions in plant canopies permits the calculation of (i) photosynthesis rates important for ecosystem and biogeochemical studies, and (ii) reflectance parameters required for remote sensing evaluation that can be used for seafloor characterization, object identification and resource mapping in optically shallow waters. The studies undertaken here have led to the development of a useful model for radiative transfer calculations in submerged plant canopies and algorithms for the retrieval of bathymetry and vegetation parameters (vegetation type and density) from hyperspectral R_{rs} imagery.

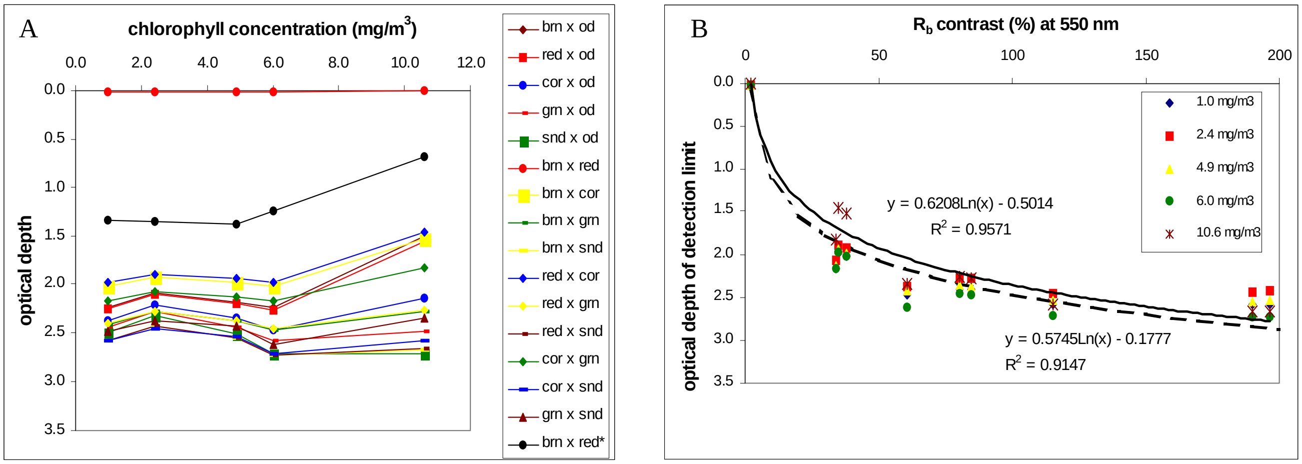

Figure 3. A. The detection limit for contrasting bottom types ranges from 2.0 to 2.5 optical depths, corresponding to about half the euphotic depth. B. Variation in detection limit among the comparisons shown in A is a logarithmic function of the contrast in target reflectance.

TRANSITIONS

All data are being prepared for transfer to the CoBOP database for archival and use by others. Ten data sets consisting of water column optical property observations of nearshore waters in Monterey Bay were transferred to J. Smart (APL, Johns Hopkins Univ) for the World Ocean Optics Database (WOOD). This project has also provided data sets to C. Davis, F. Dobbs, D. Burdige, R. Maffione, C. Mobley, W. Philpot, and P. Reid as part of various CoBOP-related collaborations. The seagrass bio-optical model has attracted considerable interest from seagrass management agencies and other scientists interested in coastal water quality and resource monitoring (see **RELATED PROJECTS**).

RELATED PROJECTS

In addition to the CoBOP collaborations described above, the seagrass bio-optical model is being utilized by the Washington State Department of Natural Resources to map potential seagrass habitat throughout Puget Sound. Their objectives are to (i) determine the status and trend of SAV resources in the region,(ii) develop a management plan that will protect existing resources and (iii) estimate water quality improvements required to expand seagrass resources in degraded habitats. The model was used in 2001 to evaluate the impact of water column phytoplankton and sediment concentrations on the distribution of eelgrass (*Zostera marina* L.) in Dumas Bay, Washington. Model predictions of eelgrass density and distribution using recently-obtained water quality data agreed very well with field observations, validating the general approach. By simulating different water column conditions with respect to phytoplankton and sediment abundance, the model demonstrated that eelgrass distributions would respond more positively to reductions in suspended sediment loads than to reductions in phytoplankton density.

The seagrass bio-optical model is also being used to evaluate an ecoengineering scheme to enhance circulation and benthic productivity of shallow embayments along the coast of Japan. This work is funded by a grant awarded the New Energy Development Organization (NEDO) of Japan. We are examining the capacity for enhancing seagrass productivity through the fertilization of these severely

CO_2-limited plants (Zimmerman *et al*. 1995; Zimmerman *et al*. 1997) with industrial flue gas generated by fossil-fuel burning electric power plants. The model is being used to predict light requirements, potential distributions and densities of seagrasses in these turbid, light-limited environments as a function of flow and degree of CO_2 enrichment.

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